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OCCURRENCE OF COHESION OF METALS DURING COMBINED
PLASTIC DEFORMATION

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OCCURRENCE OF COHESION OF METALS DURING COMBINED PLASTIC DEFORMATION

S. G. Aynbinder and E. F. Klokova

Introduction

Currently one can consider it established that cohesion of metals is an important factor in the process of dry friction [1]. The practical use of this phenomenon has begun: the so-called cold welding of metals--connection of metal items with the help of compression without any heating.

The reason for the occurrence of cohesion between clean metal surfaces with their convergence to the distance of action of interatomic forces hardly needs special explanations, however under real conditions the surfaces of the metal items are always covered with layers that prevent such convergence and cohesion. For example, there is always a cold-hardened layer formed as a result of a certain machining (cutting, rolling, polishing, etc.). Further there is a layer of oxides, finally, a layer of certain adsorbed substances. For the occurrence of cohesion of the oxides the adsorbed substances must be removed from the site of connection. During friction and cold welding this is implemented as a result of plastic deformation at the site of connection [5]. It is evident that the amount of deformation in which cohesion occurs is determined both by the physical and mechanical properties of the metals located under the layers listed above, and the properties of the films [2], and it is necessary to study the effect of the correlation of properties of the films and basic metal on the occurrence in order to understand the phenomenon of cohesion. This work has attempted to study this question with the help of simulation of the natural films of galvanized and varnished films of varying thickness and hardness. Samples were also studied with oxide films obtained by electrolytic means.

1. Technique of Study

Studies were made on samples in the form of plates 100x2.5x25 mm in size made of copper, aluminum, tin, lead and iron. Generally accepted methods were used to apply to the samples galvanized coatings made of different metals and different thicknesses (see table 1). Oxide films were also applied to the samples made of aluminum, tin and copper by electrolytic means. Varnished films made of solutions of rosin in acetone and alcohol of varying concentration were applied to the copper and tin. After application of the coatings and varnished films the samples were

not further cleaned and until the experiments were kept under normal atmospheric conditions wrapped in paper.

For a qualitative study of the process of film breakdown during combined plastic deformation the samples were compressed between two cylindrical dies 5 mm in diameter. After pressing in of the dies to a certain depth that characterizes the degree of relative deformation of the surface, the state of the surface was studied on a tool microscope. The presence of cohesion was determined according to the magnitude of the force necessary to separate the samples after compression. A quantitative determination of the ability of the given combination of base metal and surface layer to cohere was made according to the amount of deformation in which cohesion occurs during compression of the samples between symmetrically inclined dies proposed by Semenov [3]. The dies were 4 mm wide, 22 mm long. The angle at the top was 170° . A significant advantage of these dies is the possibility as a result of one-two analyses of establishing the degree of deformation in which cohesion occurs. We note that the amount of relative pressing-in of the die is a conditional characteristic for the stress state of the metal under the die is not uniaxial, while the deformation of the surface is nonuniform. Its amount is reduced from the center to the periphery. For example, during pressing in of the die to 60% of the initial thickness of the plate [6] (aluminum, plate 2 mm thick) deformation under the die center is equal to 400%, while the average deformation under the die is 160%. Consequently, the relative deepening of the die characterizes only the average deformation, and apparently, is more accurate the greater the ratio of the die diameter to the thickness of the plates.

We note that in all the studies of cold welding of metals (see [4-6]) the capacity of the metals for welding was also determined according to the relative pressing in of the dies, therefore the use of this characteristic is convenient for comparison with the data of other work. The adopted technique of the studies is not perfect. The definition of "noticeable" cohesion after compression between the cylindrical dies is not precise. In the experiments with inclined symmetrical dies the degree of pressing-in at which cohesion occurs depends on the relative dimensions of the die and the angle at the top. However, in the experiments described further where

studies were made only of the main features of the breakdown in the films and the occurrence of cohesion, the indicated shortcomings in the technique did not have important value.

2. Results of Studies

1. Deformation of the Surface Films

The nature of deformation in the surface films in the given amount of general deformation is completely defined by the correlation of hardness and plasticity of the films and the underlying metal. If the film is considerably harder than the base metal (5-6-fold) then the deformation occurs as follows: with a certain degree of pressing-in of the die cracks appear on the surface of the film (fig. 1), completely symmetrical on both samples. With further pressing-in pieces of the destroyed film are moved together with the yielding surface, themselves being little deformed due to the high relative hardness. Between the pieces of film sections of clean metal appear which with a further growth in the forces and deformations converge as a result of the extrusion of the films from the cohesion zone, as well as the pressing-in of pieces of film into the mass of the underlying metal. Figures 2 and 3 show the copper samples covered with nickel film with hardness 400 kg/mm^2 with different depths of pressing-in of the die that illustrate the process of film breakdown described above. The film of nickel, copper, chrome on aluminum, film of chrome on copper, etc. are completely broken down in the same way.

Deformation of the films occurs differently if they are softer than the underlying metal or close to it in hardness. In this case, as the experiments showed, even with very great deformation of the surface the film is not cracked, but being plastically deformed spreads together with the underlying metal. Sections of clean metal here naturally cannot appear from under the films. The films made of silver, tin, zinc on copper, oxide film on copper, film made of zinc on iron and aluminum are deformed thus.

2. Effect of Correlation of Mechanical Properties of Film and Underlying Metal on Occurrence of Cohesion

The results of experiments to study the occurrence of cohesion given

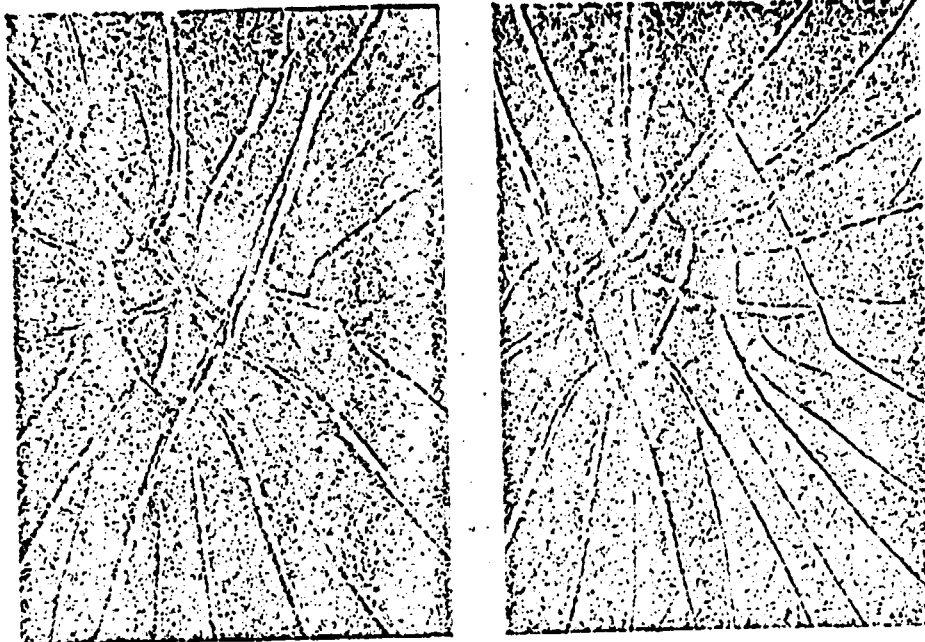


Figure 1. Film of Nickel on Copper. Starting of Compression of Die (x 15)
a. upper sample; b. lower sample.

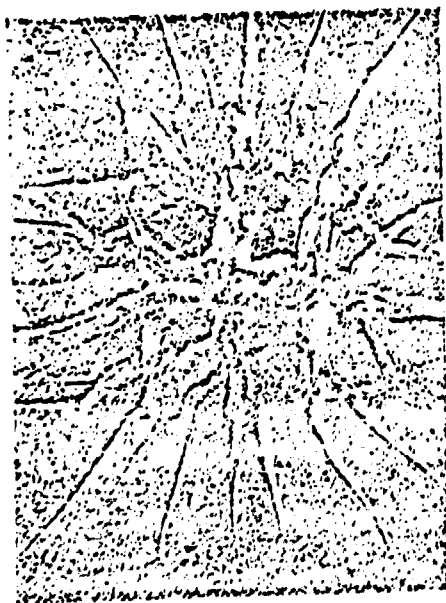


Figure 2. Film of Nickel on Copper, Deformation 30% (x 15).

in table 1 are in accordance with the nature of breakdown of the surface layers.

As is apparent from the data in the table cohesion occurs in the case where the surface of the metal is covered with a film with hardness that is considerably greater than the hardness of the metal, and does not occur with hardness of the surface layer close to the hardness of the underlying metal. It is necessary here to bear in mind that the samples after application of the coating are not further cleaned and are stored under normal atmospheric

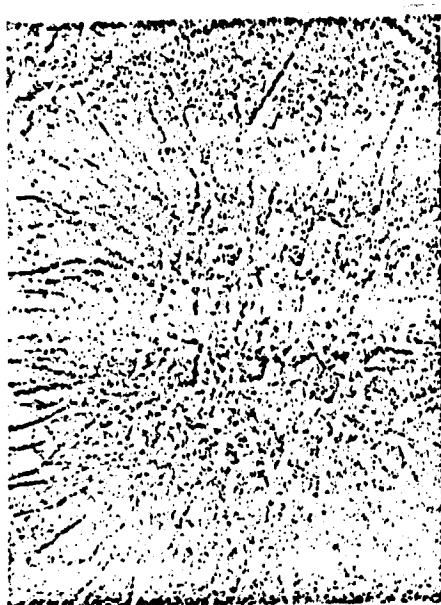


Figure 3. Film of Nickel on Copper, Deformation 50% (x 15).

conditions often for several days before the experiments were conducted. Thus, when there are on the surface very hard films of different types the contamination that appears in the process of storage does not prevent the occurrence of cohesion. Due to the development of methods for preparation of the surface for cold welding experiments were also conducted on compression of samples covered with hard films, after special contamination of the surface of the films by wiping them with hands covered with a layer of machine oil

or lubricating grease. As is known, under normal conditions such contamination completely prevents welding [5] whereupon subsequent degreasing does not yield positive results. If the contaminants are applied to solid films, for example, nickel films on copper, aluminum, chrome on copper, aluminum, etc., then cohesion occurs also in the presence of contaminants, only somewhat greater deformation is required, and with very strong contaminants--preliminary simple degreasing. Such a weak effect of contaminants in the presence of relatively hard films can be explained as follows: the films in compression are destroyed completely symmetrically and almost do not undergo plastic deformation, therefore the contamination in them with a rise in the stresses are clamped between the opposite pieces of films. The irregularities that are always present on the films create labyrinth thickenings that with sufficient thickness of the films prevent sliding of the contaminants to the newly formed clean surfaces. This will occur with fairly high specific loads at the moment of crack formation in the films. If there will be friable but low-strength films on the surface for example, varnished, then cohesion does not occur for breakdown of the films will occur with small force of pressure when the contaminants can

TABLE 1

(1) Материал образца	(2) Микротвердость образца, кг/мм ²	(3) Материал покрытия и его толщина, μ	(4) Микротвердость покрытия, кг/мм ²	(5) Результаты со- мкнутой дефор- мации (есть или нет сцепления)
Cu	55	Ni 3-40 Cr 9-25 Zn 15-20 Cu 15 Ag 20 Sn — Лак(6) — Оксидная пленка(7) —	500-700 250-450 70-75 170 65 — —	Есть(8) Нет(9) " " " "
Al	23	Ni 10-15 Cu — Cr — Оксидная пленка(7) —	600 170 400 200	Есть(8) " " "
Sn	2	Ni — Оксидная пленка(7) — Лак(6) —	500 — —	Есть(8) Нет(9)
Fe	130	Ni 18-25 Cr 15-20 Sn — Cu 10 Zn 4-30	500-700 400 — 170 70	Есть(8) Нет(9) " "
Pb	1.5	Ni 10-30	400	Есть(8)

1. Material of sample
2. Microhardness of sample, kg/mm²
3. Material of coating and its thickness, μ
4. Microhardness of coating, kg/mm²
5. Results of combined deformation (there is or there is not cohesion)
6. Varnish
7. Oxide film
8. there is
9. there is not

easily fall on the appeared clean surfaces.

3. Order of Cohesion

In order to determine the effect of the metal nature on the occurrence of cohesion the degree of deformation was defined that is necessary for occurrence of cohesion of different metals on the condition that the surface has a film with hardness much greater than the hardness of the actual metal. Compression was carried out between the inclined-symmetric dies. The

results of the experiments are given in table 2.

As is apparent from the data in the table the studied metals are coupled roughly with the same deformation, and the order of cohesion, i.e., the varying degree of deformation for the different metals that is usually given in the literature is not obtained (see below).

TABLE 2

(1) Материал образца	(2) Материал пленки	(3) Степень де- формации при возникновении сцепления, %	(4) Относительная твёрдость пленки
Al	Ni	51	25
Cu	Оксид	50	—
Pb	Cr	50	6
Sn	Ni	50	250
	Ni	50	125
	Оксид(3)	58	—

1. material of sample
2. material of film
3. degree of deformation during occurrence of cohesion, %
4. relative hardness of film
5. oxide

3. Discussion of Experimental Results

As a result of the studies of recent years on the processes of dry friction and cold welding of metals it was established that different metals require varying deformation for the occurrence of cohesion. For example in [3] the order of cohesion mentioned above is given in which the metals are arranged as indicated in table 3 according to the amount necessary for the occurrence of cold welding of deformation.

Such a difference in the degree of deformation is attributed to the physical peculiarities of different metals [7]. To explain the process of the occurrence of cohesion different qualitative theories are enlisted, for example, recrystallization [10] or energy [3]. These theories do not take into account the real structure of the metal surfaces and hardly can correctly explain the phenomenon of the emergence of cohesion of metals. Their critical examination is given in publication [2].

Bearing in mind the results of the experiments described above, we

TABLE 3

Металл (1)	(2) Остаточная толщина, %
Алюминий (3)	40-30
Дюралю (4)	20
Кадмий (5)	16
Свинец (6)	16
Медь (7)	14
Никель (8)	11
Цинк (9)	8
Серебро (10)	6
Олово (11)	10

1. metal
2. residual thickness, %
3. aluminum
4. duralumin
5. cadmium
6. lead
7. copper
8. nickel
9. zinc
10. silver
11. tin

TABLE 4

(1) Материал образца	(2) Микро-твердость в исходном состоянии, кг/мм ²	(3) Микро-твердость после обработки стальной щеткой, кг/мм ²
Al	23	114
Cu	55	180
Fe	130	600
Ag	90	145
Ni	210	550
(*) Латунь	95	210

1. material of sample
2. microhardness in initial state, kg/mm²
3. microhardness after treatment with steel brush, kg/mm²

will try first of all to give an explanation of the formation of the order of cohesion. As is known [3,5- when conducting experiments on cohesion the compressible surfaces are cleaned either by calcination at temperatures 300-600°C, or with the help of a rotating metal brush.

During cleaning by metal brush a solid and friable layer is formed on the surface [2] apparently consisting of cold-hardened and oxidized metal. Table 4 presents the values of microhardness of the initial metal and the layer formed during purification.

As is apparent from the data in table 4, the relative hardness of the layer is different in different metals. We will compare the data on the relative hardness of the surface layer with the degree of deformation necessary for the occurrence of cohesion.

As is apparent from the data of table 5 the degree of deformation is greater the lower the relative hardness of the layer, i.e., is governed by the correlation of the mechanical properties of the surface layer and

the underlying metal as in the experiments described above with galvanized films.

TABLE 5

Material of sample	Relative hardness of film	Residual thickness during occurrence of cohesion, %
Al	5	40-30
Cu	3.3	14
Ni	2.6	11
Ag	1.6	6

TABLE 6

Material of sample	Relative hardness of oxides	Residual thickness, %
Al	4.5	40
Cd	1.5	16
Pb	1.3	16
Cu	1.2	14

During cleaning by calcination different fatty contaminants are removed but the thickness of the oxide layer, naturally, increases. We will compare the relative hardness of the oxides [3] with the amount of deformation in which cohesion occurs.

As is apparent from table 6, also in this case the degree of deformation is inversely proportional to the relative hardness.

Thus, the peculiarities in the metals from the viewpoint of their capability for cohesion are defined by the relative mechanical properties of their oxides. There is foundation to hypothesize that the mechanical properties of the oxide films depend also on their thickness. For example, Chertavskikh [9] indicates that the greater the thickness of the oxide film the greater the magnitude of the friction force during broaching. Apparently, from this it follows that an increase in the thickness of the film results in facilitation of its breakdown. Possibly this is linked to the known scale effect of strength. If this is so, then calcination yields not only purification from contaminants, but also promotes a reduction in the degree of necessary deformation as a consequence of the thickening of the film of oxides and increase in its brittleness.

Thus, both the experiments with samples covered by galvanized films with varying relative hardness, and the experiments with samples covered

with films formed as a result of the treatment by rotating metal brush or calcination demonstrate that the emergence of cohesion between two compressible surfaces is defined by the correlation of mechanical properties of the surface films and the underlying metal. If the surface layer is harder and less plastic than the underlying metal, then with a certain force and degree of deformation this layer begins to crack and break down, whereupon completely symmetrically on both surfaces; further the pieces of film are moved together with the surfaces that are cracked as a consequence of deformation; between them a metal appears that is free of contaminants, on this metal the cohesion occurs with the corresponding convergence. The amount of deformation in which cohesion occurs in the first approximation is determined by the correlation of hardness of the films and the underlying metal and is lower the greater this ratio. Apparently, there is a certain limit magnitude of this ratio, and its further increase will not produce a reduction in deformation (see table 2). If the hardness of the films is equal to or close to the hardness of the underlying metal, then their breakdown during plastic deformation does not occur, the clean metal does not appear, and the cohesion cannot occur. The cohesion for the films on large sections is also impossible for the contaminants that are always on the surface are cracked together with the films located under them and prevent cohesion.

We note that the mechanism for the occurrence of cohesion during plastic deformation of micro-irregularities in the process of friction basically cannot differ from the process described above. Quantitative differences will occur due to the presence of tangential forces, as well as with an increase in temperature in the process of friction that produce a growth in the thickness of the films of oxides and change in the mechanical characteristics of the films and the metal of the base. The stated mechanism for the occurrence of cohesion makes it possible to explain certain phenomena that occur during friction. For example, currently "lubrication" with soft plastic metal is becoming ever more widely used in the operation of bearings under severe conditions. Bowden [10] believes that the advantages of this lubrication consists of the low resistance

to destruction of the bridges of welding that occur during friction on the soft metal; however it is possible that the main role of lubrication in the form of a soft metal consists of prevention of the occurrence of bridges of welding between the hard bases of the bearings. The occurrence of cohesion with respect to the lubricant is determined by the properties of its oxides.

With large specific loads and in the presence of lubrication often jamming occurs which leads to catastrophic wear. The reason for the appearance of jamming is easily explained if one considers that on the surface of the bearing there is always a hard layer of cold-hardened metal and a layer of oxides growing with a rise in temperature. With fairly great specific pressures these layers can be destroyed, and in this case even the presence of a lubricant does not protect it from jamming. Since during friction the surface layers are affected not only by normal but also tangential forces, then this cannot help but facilitate the breakdown of these layers. Here it is necessary only to bear in mind that a certain minimum normal pressure is necessary to prevent sliding of the lubricant or contamination on the clean layers of metal that appear after breakdown of the surface layers.

From the presented viewpoint the increase in the hardness of the metal must result in a decrease in the cohesiveness due to the decrease in the relative hardness of the surface layers.

Conclusions

1. Experiments were conducted to study the cohesion of metals in the presence on their surfaces of films of varying thickness and hardness. It was established that the deformation necessary for the occurrence of cohesion is determined by the correlation of mechanical properties of the films and the base metal. The greater the relative hardness of the film the lower, to certain limits, the deformation necessary for the occurrence of cohesion. The films that are as plastic as the base metal prevent cohesion, since in this case it is impossible for sections of metal to appear that are free of contaminants. Apparently the physical peculiarities of metals that determine their capability for coalescence under conditions of dry friction are the relative hardness and plasticity of the films of

oxides formed on their surface under atmospheric conditions, as well as to a certain degree their cold-hardening, the capability for strengthening.

2. An explanation is given of the phenomenon of lubrication by soft metal consisting of the fact that in this case coalescence of the harder metal of the bearing is prevented.

3. An explanation is suggested for the phenomenon of jamming with great specific loads and the presence of lubrication.

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